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Advanced Cast Aluminum Alloys

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Abstract

A recent advancement in cast aluminum alloys has demonstrated that complex shapes can be cast from a microalloyed Al-Cu alloy in dry sand molds with chills and that these castings can be heat treated to produce mechanical and physical properties nearly comparable to wrought 2519 aluminum alloy. Given this initial level of success, further research has been focused on improving this microalloyed Al-Cu alloy so that the mechanical properties consistently meet or exceed those of wrought 2519 alloy. Further, new research has been initiated on ultra-high strength, microalloyed Al-Zn-Mg-Cu alloys with the goal of producing complex castings with properties significantly better than wrought 2519 aluminum alloy and equivalent to or better than the best 7000 series wrought alloys. The development of the appropriate chemistries, casting practices and heat treatments are described in this paper.

Introduction

Wrought aluminum alloy RSA 708 [1] is the highest strength commercially available aluminum alloy and is produced by rapid solidification (melt spinning) followed by extrusion. This production route has demonstrated that aluminum alloys with yield strengths in excess of 690 MPa with good elongation (reportedly 8%) are possible. Wrought 7055 aluminum alloy is the highest strength conventionally processed, commercially available, wrought aluminum alloy [2]. The yield strength of this alloy is less than the rapidly solidified alloy but still about 50% higher than wrought 2519 aluminum alloy. However, the entire 7000 series of aluminum alloys have poor-to-fair general corrosion resistance and poor-to-good stress corrosion cracking resistance. Wrought 2519 aluminum alloy has good strength, good ballistic performance, good stress corrosion cracking resistance but only fair general corrosion resistance. Despite the fair general corrosion resistance, wrought 2519 aluminum alloy is currently used for General Dynamic's amphibious Expeditionary Fighting Vehicle [3]. Wrought 5083 aluminum alloy is widely used for lightweight military armor applications, has good general corrosion resistance but low strength. Wrought 7039 aluminum alloy is starting to be used for lightweight military armor applications, has good stress corrosion cracking resistance but poor general corrosion resistance. BAC of VA, LLC developed a modified version of wrought 2519 aluminum alloy called BAC 100™, a casting production process and thermal mechanical treatments that produce shaped components nearly comparable to the strength and ballistic performance of wrought 2519 aluminum alloy [4]. Preliminary studies with cast aluminum alloys containing zinc, magnesium and copper have demonstrated that high strength is possible but the tensile ductility has been unacceptably low and needs to be significantly improved. Table 1 is a comparison of the properties of the above mentioned materials.

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14. ABSTRACT
A recent advancement in cast aluminum alloys has demonstrated that complex shapes can be cast from a microalloyed Al-Cu alloy in dry sand molds with chills and that these castings can be heat treated to produce mechanical and physical properties nearly comparable to wrought 2519 aluminum alloy. Given this initial level of success, further research has been focused on improving this microalloyed Al-Cu alloy so that the mechanical properties consistently meet or exceed those of wrought 2519 alloy. Further, new research has been initiated on ultra-high strength, microalloyed Al-Zn-Mg-Cu alloys with the goal of producing complex castings with properties significantly better than wrought 2519 aluminum alloy and equivalent to or better than the best 7000 series wrought alloys. The development of the appropriate chemistries, casting practices and heat treatments are described in this paper.

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Table 1. Property Comparison of Some Aluminum Alloys

Alloy	Form	Yield Strength, MPa	Hardness, BHN	General Corrosion Resistance	Stress Corrosion Cracking Resistance
5083	plate	198-280 typ	81-93 typ	excellent	good
A356-T6	casting	210 min	90 min	good	na
High Toughness Al-Cu alloy	casting	330 typ	110-130 typ	na	good (~207 MPa)
7039-T64	plate	380 typ	133 typ	poor	good
High Strength Al-Cu alloy	casting	400 typ	130-140 typ	na	good (~275 MPa)
2519-T87	plate	400 min	130 min	fair	good
Al-Zn-Mg-Cu alloy	casting	>493	>160	na	na
7055-T7751	plate	614 typ	na	fair	poor (103 MPa)
RSA 708 T6	extrusion	700 typ	230 typ	na	na

Wrought aluminum alloys (such as 5083, 2519, 7039, 7055, etc) can provide a desirable combination of properties, but, wrought alloys are only available in plate or billet form. Extensive machining of a plate or billet, which is time consuming, costly, and generally restricted to relatively simple shapes that do not have internal passageways, is required to produce a structural component from these alloys. Advanced aluminum casting alloys with enhanced mechanical, physical and ballistic properties would solve this problem. The inherent design flexibility of the casting process would allow for near-net shape structural components to be manufactured with significant cost and weight savings over traditional wrought aluminum alloys. In addition, the ability to cast complex shapes would allow the integration of a number of parts into a single component and thus eliminate expensive weldments and assemblies.

Microalloyed Aluminum-Copper Alloys

Alloy Concept. A new family of microalloyed aluminum-copper alloys was developed in 2005 [4] with improved mechanical properties and improved resistance to hot tearing compared to aluminum alloys 201 and 206. During the development of this new alloy, laboratory experiments were performed to determine the effects of seven potential alloying elements (Cu, Ag, Cr, Mg, Mn, V, Zr). Concurrently, trials were run at a production foundry to determine castability and hot tearing tendency. Both high toughness and high strength variants of this alloy were developed.

Experimental Methods. Twenty-three, 1.1 kg (2.5 lb) heats of microalloyed Al-Cu alloys were made with P1020 ingot (commercially pure aluminum), Al-50%Cu master alloy, Al-20%Cr master alloy, Al-25%Mn master alloy, Al-5%V master alloy, Al-5%Zr master alloy, pure Mg ingot and pure Ag ingot. The metal was melted in a crucible, grain refined with either Al-5%Ti-1%B or Al-3%Ti-1.5%C and poured into Y-blocks that had a copper chill for the base. A spectrometer sample was also poured from each heat. The Y-blocks were hot isostatically pressed (HIP) at 510-524C (950-975^{o}F) and 103 +/- 3.4 MPa (15,000 +/- 500 psi) for 2-3 hours at a commercial HIP'ing service center. The Y-blocks were then sectioned and the samples heat treated to produce the T4, T6 or T7 temper. The solution treatment was 510-516^{o}C (950-960^{o}F) for 2-4 hours followed by 529-535^{o}C (985-995^{o}F) for 16-20 hours then quench in warm water at

60-82^{o}C (140-180^{o}F). For the T4 temper, samples were allowed to age at room temperature for a minimum of 7 days. For the T6 temper, samples were aged at room temperature for a minimum of 24 hours followed by artificial aging at 160-166^{o}C (320-330^{o}F) for 30 hours. For the T7 temper, samples were aged at room temperature for a minimum of 24 hours followed by artificial aging at 196-202^{o}C (385-395^{o}F) for 24 hours. The samples were then machined into tensile bars and tested in accordance with ASTM E-8. Samples were also prepared using standard metallographic techniques and then examined on a Philips 515 scanning electron microscope equipped with an energy dispersive X-ray spectrometer. Semi-quantitative elemental analysis was performed on the particles present.

To evaluate castability in a production environment, a complex 4.3 kg (9.5 lb) seat frame casting was produced. Molds were made from chemically bonded lake sand. Insulated riser sleeves and steel chills were incorporated into the molds. Production quantity heats of 275 kg (600 lbs) were produced from selected alloys, degassed with argon for 10-12 minutes, grain refined with either Al-5%Ti-1%B or Al-3%Ti-1.5%C and molds poured at 721-754^{o}C (1330-1390^{o}F). Castings were examined for hot tears and then the castings were HIP'ed, heat treated and sectioned for determination of mechanical properties. The mold and castings are shown in Figures 1a&b.

(a) seat frame casting being poured

(b) seat frame castings after shake-out

Figure 1. (a) Seat frame casting being poured in a production foundry and (b) castings after shake-out.

Results & Discussion. The laboratory experiments revealed the individual effects of seven elements. Cu did not have strong effect on mechanical properties. Ag had a strong positive effect on UTS and YS in the T6 and T7 tempers (as expected) but no effect on mechanical properties in the T4 condition. Cr and Mg had a negative effect on mechanical properties in all tempers. Mn had a positive effect on UTS and YS in the T4 temper and the unusual effect of increasing UTS and elongation while decreasing YS in the T6 and T7 tempers. V, in general, had a negative effect on mechanical properties except for improving elongation in the T6 and T7 tempers. Zr had a positive effect on all mechanical properties in all tempers. The results of the laboratory experiments are shown in Table 2.

Table 2. Results of Laboratory Experiments to Determine the Individual Effects of Seven Elements on the Mechanical Properties of an Al-Cu Alloy in the T4, T6 and T7 Tempers.

		T4			T6			T7		
Element	Range, wt%	UTS	YS	El	UTS	YS	El	UTS	YS	El
Cu	4.5-6.7						-		+	-
Ag	0-0.40				+	+	-	+	+	
Cr	0-0.50	-		-	-	-	-	-	-	-
Mg	0.1-0.80	-		-	-		-	-	-	-
Mn	0.1-0.65	+	+		+	-	+	+	-	+
V	0-0.25	-	-	-	-		+	-	-	+
Zr	0-0.25	+	+	+	+	+	+	+	+	+

Basically, this new alloy is based on the Al-Cu system, which is known to produce high strength and high toughness, coupled with dispersoid strengthening concepts which improve yield strength without reducing ductility. Further, undesirable alloy interactions were accounted for and minimized. Two variants of this alloy were developed, high toughness and high strength. A typical chemistry for this alloy is listed in Table 3. The high toughness variant was produced by reducing the Cu content to less than about 5.60 wt% and eliminating the Ag addition. For the high strength variant, Cu content could be higher and up to 0.40 wt% Ag was added.

Table 3. Typical Chemistry for Microalloyed Al-Cu Alloy.

Element	Cu	Mg	Mn	Ti	V	Zr	Ag	Fe	Si
Wt%	5.73	0.22	0.32	0.07	0.09	0.20	0.20	0.12	0.01

The microalloyed Al-Cu alloy with the chemistry of Table 3 had a liquidus temperature of 640°C (1184°F), a small arrest at 552°C (1026°F) and a solidus temperature of 530°C (986°F). The freezing range for this alloy was 110°C (198°F), which is considered "long". The cooling curve for the microalloyed Al-Cu chemistry listed in Table 3 is shown in Figure 2.

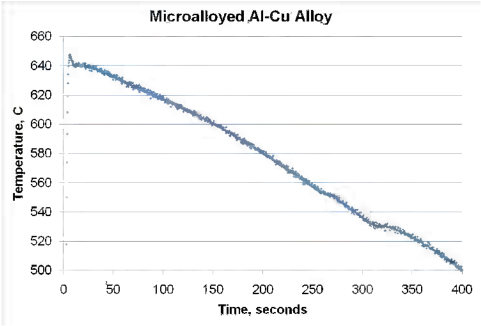
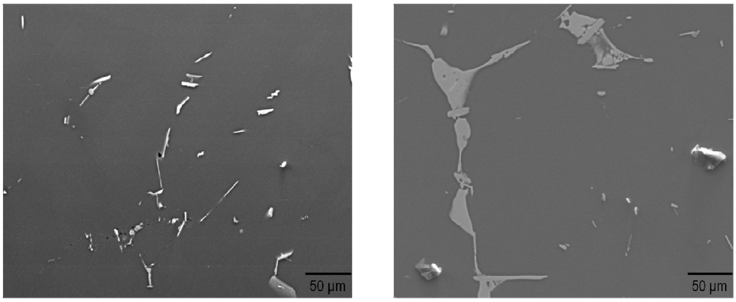


Figure 2. Cooling curve for microalloyed Al-Cu alloy showing a liquidus temperature of 640°C (1184°F), a small arrest at 552°C (1026°F) and a solidus temperature of 530°C (986°F).

The seat frame casting revealed that hot tearing tendency was a strong function of Cu content. Castings with a Cu content less than 5.3 wt% exhibited hot tearing and castings with a Cu

content in excess of 5.3 wt% exhibited no hot tearing. A206 alloy castings (Cu content < 5.3 wt%) were also poured and all of these castings exhibited severe hot tearing.

The microstructure of the microalloyed Al-Cu alloys may contain "large" particles (up to 50 μm long) after heat treatment. The largest particles were $CuAl_2$ and the smaller particles generally contained Cu, Fe and Mn. The microstructure of this alloy is shown in Figures 3a&b.



(a) (b)

Figure 3. Microstructure of microalloyed Al-Cu alloy after HIP'ing and heat treatment (T6 temper). (a) shows the generally small size of the particles present after heat treatment and (b) shows a cluster of large, interdendritic $CuAl_2$ particles that were not completely dissolved during the solution heat treatment.

Aluminum-Zinc-Magnesium-Copper Alloys

Alloy Concept. The 7000 series aluminum alloys have the highest strength for wrought aluminum alloys. Building upon the success with the Al-Cu alloys, a program was initiated to determine the feasibility of producing an aluminum casting alloy with significantly better mechanical properties based on the aluminum-zinc-magnesium-copper system. In this study, the ratio of Zn to Mg was chosen to maximize strength (high zinc content) and minimize excess magnesium. Assuming that the strengthening precipitate is Zn_2Mg [5], the calculated "ideal" Zn to Mg weight ratio was 5.39. The ratio of Zn to Mg for commercial 7000 series aluminum alloys was 1.43-4.28, which indicated an excess of Mg. The ratio of Zn to Mg for rapidly solidified commercial aluminum alloys was 2.20-4.78, which also indicated an excess of Mg. The addition of copper has been reported to increase strength but decrease general corrosion resistance if >3 wt% [5]; so, a target maximum of 2 wt% copper was chosen. According to the equilibrium phase diagram [6], an addition of 2 wt% Cu should go completely into solid solution above ~425°C (800°F) and then reprecipitate during low temperature aging at 120°C (250°F). Past experience with zirconium demonstrated improved strength and ductility in Al-Cu alloys [4], so a target of 0.15-0.25 wt% Zr was chosen.

Experimental Methods. Five, 9 kg (20 lb) heats of Al-Zn-Mg-Cu alloys were made with P1020 ingot (commercially pure aluminum), ZA27 ingot, Al-50%Cu master alloy, Al-10%Zr master alloy and pure Mg ingot. The alloys were melted in a SiC crucible, degassed with nitrogen for 2-3 minutes, grain refined with an addition of 1.8 grams of Al-3Ti-1B per kg of alloy and then poured at 704-718°C (1300-1325°F). A thermal analysis sample and a spectrometer sample were poured from each heat. The liquidus, solidus and chemistry of each heat are listed in Table 4.

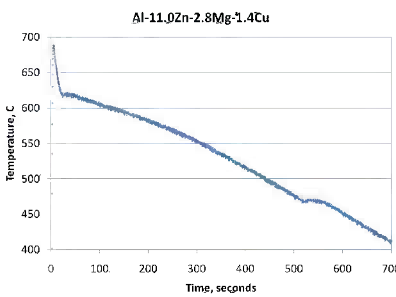
The alloys were cast in chemically bonded sand Y-block molds with a steel chill for the base. The cast samples were solution treated at 454°C (850°F) for up to 24 hours, quenched in warm water, aged at room temperature for 24 hours and then artificially aged at 120°C (250°F) for 24 hours. Samples were prepared using standard metallographic techniques and then examined on a Philips 515 scanning electron microscope equipped with an energy dispersive X-ray spectrometer. Semi-quantitative elemental analysis was performed on the particles present.

Table 4. Chemistry* of Cast Al-Zn-Mg-Cu Alloys (wt %).

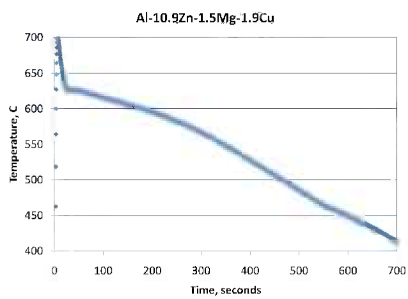
Heat No.	Zn	Mg	Cu	Zr	Liquidus, °C	Solidus, °C	Length of Solidus Reaction, seconds
1	10.93	1.46	1.93	0.14	627	462	7.25
2	10.57	2.13	1.87	0.14	623	467	20.25
3	11.02	2.77	1.41	0.12	620	470	39.50
4	8.95	2.30	0.92	0.18	628	471	18.25
5	7.97	1.76	1.58	0.10	629	467	11.75

* determined by NSL Analytical, Cleveland, OH

Results & Discussion. The Al-Zn-Mg-Cu alloys investigated had a very long freezing range and formed an interdendritic network of Zn-Cu-Mg-Al particles due to segregation of alloying elements during solidification. Microporosity was also present in all of the samples because of the long freezing range and lack of isothermal solidification. Surprisingly, the liquidus and solidus temperatures did not show a large variation despite the Zn-content varying from 8-11 wt%, the Mg-content varying from 1.5-2.8 wt% and the Cu-content varying from 0.9-1.9 wt%. However, the length of the solidus reaction varied significantly (from 7.25-39.5 seconds). The best correlation between chemistry and the length of the solidus reaction was the Mg content (higher Mg content produced long solidus reaction time). Suppressing the segregation of alloy elements would assist in achieving good mechanical properties. Cooling curves for the Al-11.0Zn-2.8Mg-1.4Cu and Al-10.9Zn-1.5Mg-1.9Cu alloys, which had long and short lengths of solidus reaction respectively, are shown in Figures 4a&b.



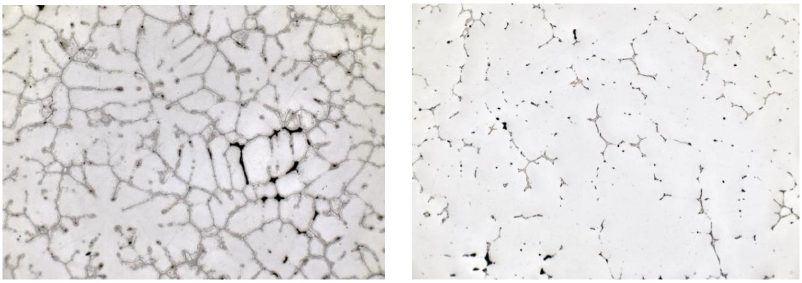
(a) Al-11.0Zn-2.8Mg-1.4Cu



(b) Al-10.9Zn-1.5Mg-1.9Cu

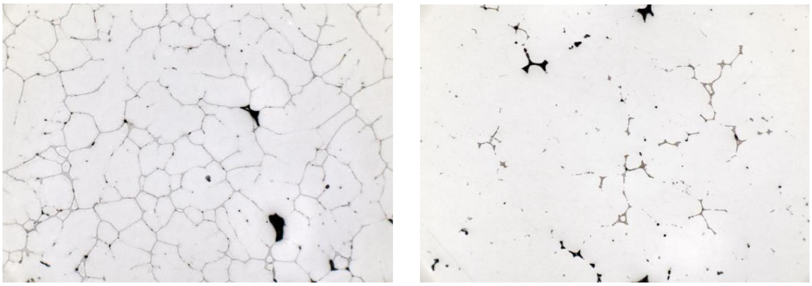
Figure 4. (a) Cooling curve for Al-11.0Zn-2.8Mg-1.4Cu alloy showing a liquidus at 620°C and a solidus at 470°C and a "long" solidus reaction time of 39.5 seconds. (b) Cooling curve for microalloyed Al-10.9Zn-1.5Mg-1.9Cu alloy showing a liquidus at 627°C, a solidus at 462°C and a "short" solidus reaction time of 7.25 seconds.

The as-cast microstructure of the Al-Zn-Mg-Cu alloys was similar to the as-cast microstructure of 7000 series aluminum ingots [8]. The heat treatment study revealed that the as-cast interdendritic network was not completely dissolved using a solution treatment temperature of 454^{o}C and a time of 24 hours; additional work is needed to determine the required heat treated to completely eliminate these particles. For the 10.6Zn-2.1Mg-1.9Cu alloy, SEM analysis determined that the predominant intermetallic particles present at the interdendritic boundaries contained Zn, Cu, Mg and Al. There were lesser amounts of two other intermetallic particles; one contained high amounts of Fe and the other contained Al and Cu, presumably $CuAl_2$. After heat treatment, the chemistries of the remaining intermetallic particles were the same, i.e., none of the phases were completely redissolved. For the 9Zn-2.3Mg-0.9Cu alloy, SEM analysis determined that the predominant intermetallic particles present at the interdendritic boundaries contained Zn, Cu, Mg and Al. Also, there was one other type of intermetallic particle that contained high amounts of Fe. The Al and Cu containing intermetallic particles were not present for this composition. After heat treatment, the chemistries of the remaining intermetallic particles were the same, i.e., none of the phases were completely redissolved. Figures 5 and 6 show the as-cast and heat treated microstructures of two of the alloys investigated.



as-cast heat treated for 24 hours

Figure 5. Al-10.6Zn-2.1Mg-1.9Cu as-cast and heat treated microstructures. The Zn-Cu-Mg-Al intermetallic particles present in the as-cast condition were not completely eliminated after 24 hours at 454^{o}C.



as-cast heat treated for 24 hours

Figure 6. Al-9Zn-2.3Mg-0.9Cu as-cast and heat treated microstructures. The Zn-Cu-Mg-Al intermetallic particles present in the as-cast condition were not completely eliminated 24 hours at 454^{o}C.

Little work has been done on determining mechanical properties since the desired microstructure (no massive intermetallic particles) has not been obtained. However, it has been determined that the yield strength of the Al-10.9Zn-1.5Mg-1.9Cu alloy was greater than 493 MPa and the hardness was 165-170 BHN (500 kg load, 10 mm diameter ball), Table 1. The strength and hardness of this cast alloy were significantly higher than wrought alloys 7039 and 2519. However, the tensile ductility was unacceptably low (essentially zero). Presumably, the reason for the low ductility was the combination of microporosity and Zn-Cu-Mg-Al intermetallic particles.

Future work will include HIP'ing and pressure solidification to eliminate porosity, optimized heat treatment to eliminate the Zn-Cu-Mg-Al intermetallic particles and chemistry optimization to minimize and/or eliminate the Zn-Cu-Mg-Al intermetallic particles in the as-cast condition.

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